Asymmetric thin current sheets in the Earth's magnetotail.

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[1] In a frame of self-consistent model of thin current sheets (TCSs), where the tension of magnetic field lines is balanced by the inertial force of ion motion, we investigated the influence of the asymmetry of plasma sources on the structure and spatial localization of the equilibrium solution. For simplicity only one ion source is considered. It is shown that the asymmetry of plasma sources does not modify dramatically the bulk of the current carried by ions at meandering orbits. Negative diamagnetic currents are significantly stronger at the side of a plasma source due to enhanced plasma density in this region. The center of TCS is displaced to the opposite side of the plasma source to keep the pressure balance. One could speculate that this phenomenon might be a cause of flapping motions of the TCS due to the natural variability of plasma sources.
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1. Introduction

[2] Measurements of ISEE-1,2, Geotail and Cluster [e.g., *Sergeev et al.*, 2003; *Asano et al.*, 2005; *Runov et al.*, 2006] revealed that thin current sheets (TCSs) in the Earth's magnetosphere might have a complicated multiscale structure and temporal dynamics. It is supposed that these current sheets appear in the magnetotail at distances about 15–20 R_e as a result of a thinning of the originally relatively thick current layer [*Sergeev et al.*, 1993]. After a period of relative quietness, the thin metastable current sheet might be destabilized [*Lui*, 1996] and sometimes even explosively [*Galeev et al.*, 1986]. This process is accompanied by energy release and various subsequent substorm manifestations.

[3] It was shown recently [*Runov et al.*, 2006] that TCSs are often very different from the well known Harris's current sheet which has identical profiles of plasma and current densities. As a rule, very thin current sheets are embedded in a thicker plasma sheet [*Sergeev et al.*, 1993]. The statistical analysis by Cluster spacecraft in July–October 2001 at a distance about 19 R_E allowed to identify three basic types of current sheet (CS) profiles: center-peaked, bifurcated and asymmetric.

[4] In some cases the position of a maximum of current density does not coincide with the minimum of the magnetic field, as it happens for bifurcated CSs with two maxima of the current density at CS edges. Experiments often points on the asymmetry of CS in the north-south direction [*Runov et al.*, 2006]. Such asymmetry is not a unique feature of the Earth's magnetotail. Similar non-symmetrical current sheet profiles were identified also in a Mercury magnetotail during Mariner 10 flybys in 1974–1975 [*Whang*, 1977].

[5] What are the factors that determine such asymmetry of current profiles? Should it necessary be related only with the peculiarities of the planetary dynamo? How do the properties of plasma sources (e.g. in the mantle or ionosphere) influence the structure of the current sheet? What could be the differences in dynamics of the symmetrical and non-symmetrical current sheets? In this work we tried to answer some of the abovementioned questions.

2. Quasiadiabatic Model of Thin Current Sheet

[6] We developed here a self-consistent model of equilibrium current sheet, where the tension of magnetic field lines in the Sun-Earth direction is balanced by the centrifugal force which acts on charged particles moving in a curved 2*D* magnetic field $\vec{B} = \{B_x(z), 0, B_z\}$ with a small normal constant component $B_z/B_{x0} \ll 1$ ($B_x(\pm\infty) = \pm B_{0x}$; we use here the standard GSM system of coordinates) [*Zelenyi et al.*, 2000, 2004a; *Sitnov et al.*, 2000].

[7] The earlier models assumed the symmetry of plasma sources populating the CS and conservation of Speiser invariant $I_z = (1/2\pi)\oint m v_z \, dz$ which makes the system integrable and the entire problem treatable analytically [*Sitnov et al.*, 2000; *Zelenyi et al.*, 2000]. In this paper we want to consider the effects of the violation of another assumption in the model concerning the north-south symmetry of the system. Really, the southern and northern mantles are not always symmetric in the Earth's magnetotail, e.g. due to tilt of the Earth's magnetic dipole at the winter and during summer these mantles are exposed differently to the solar wind. The asymmetry in the mantle might also depend on 3D reconnection pattern in the high-latitude magnetosphere.

[8] To simplify the problem we will consider the extreme case when only one plasma source, say in the northern hemisphere (see Figure 1), is operating to support the 1D quasiadiabatic CS equilibria.

[9] We assume that electrons are forming the cold neutralizing background and does not contribute significantly to the cross-tail current. Our earlier results when electron contributions have been explicitly taken into account [*Zelenyi et al.*,

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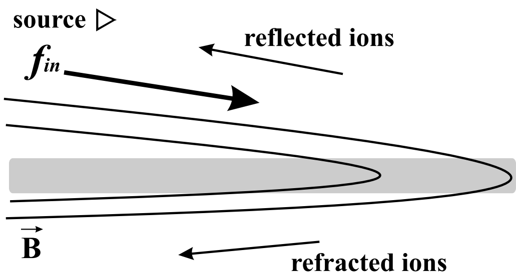

Figure 1. Scheme of the formation of asymmetric CS.

2004a] show that it is a very reasonable assumption for realistic parameters of the current sheet ($T_e/T_i \leq 1/5$, B_z / $B_{x0} \geq 10^{-2}$). Consequently the influence of ambipolar electrostatic fields will be also neglected in this study.

[10] We will consider simple 1D model of CS (taking into account only z-dependence of all CS parameters). The choice of deHoffmann-Teller frame of reference allows us to transform away the dawn-dusk component of the electric field E_y. The dynamics of ions, which become demagnetized in a central region of CS, might be described in a frame of quasiadiabatic approximation [*Büchner and Zelenyi*, 1989] which allows the approximate conservation of I_z due to the smallness of so called parameter of adiabaticity $\kappa = \sqrt{R_c/\rho_L}$, where R_c is the minimum curvature radius of the magnetic field line, ρ_L is the maximum Larmor radius of ions.

[11] Trajectories of non-adiabatic particles very sensitively depend on phases of their motion at the moments when they enter the immediate vicinity of the current sheet. If particles enter field reversal plane from the north, their destiny, i.e. whether it will return to the northern hemisphere or will move to the south depends on the phase gain of the fast motion across field reversal plane between separatrix crossings. This bifurcation of trajectories was illustrated even in an earlier work by *Speiser* [1965] and quantitatively described in the paper by *Büchner and Zelenyi* [1989], that have shown that this phase difference $\Delta\theta$ is a function of B_z. A good deal of attention was devoted to so called CS resonances when $\Delta\theta = \pi N$ and the next effect of chaotic scattering effectively is very small [*Chen*, 1992; *Walker et al.*, 2004].

[12] In the analysis below we will follow a more simple approach introducing coefficient of reflection r which describes the probability of particle "reflection" from CS to the same hemisphere, while the probability of refraction will be correspondingly $(1 - r)$. In reality the meaning of this phenomenological coefficient r is rather complicated, because it depends on the shape of original distribution function and value of the B_z component of magnetic field. For the original distributions with relatively strong anisotropy (see below), which have narrow dispersion in energy and pitch angles [*Zelenyi et al.*, 2004a] such simplified approach is well justified and allows us to construct a set of Vlasov equilibria with an arbitrary degree of their asymmetry. The limiting $r = 0$ case corresponds to even $\Delta\theta = 2\pi N$ CS resonances, while $r = 1$ to the odd ones when $\Delta\theta = (2N + 1)\pi$. Our approach nevertheless allows also to consider the intermediate cases $0 < r < 1$.

3. Basic Equations

[13] The model of asymmetric CS discussed in this paper is the generalization of our previous theoretical models having two symmetric mantle plasma sources in both northern and southern hemispheres [*Zelenyi et al.*, 2004a, 2004b]. The Vlasov-Maxwell system of equation is used to find the equilibrium solution.

$$\frac{dB_x}{dz} = \frac{4\pi e}{c} \int\limits_{\{\vec{v}\}} v_y f(\vec{v}, \vec{r}) d^3\vec{v} \tag{1}$$

[14] The distribution function in the northern ($z \geq 0$) and southern ($z < 0$) lobes might be written in the following form discussed in a previous section:

$$f_{z\geq 0} = \begin{cases} f, v_\parallel \leq 0 \\ rf, v_\parallel > 0 \end{cases}, \quad f_{z<0} = \begin{cases} (1-r)f, v_\parallel \leq 0 \\ 0, v_\parallel > 0 \end{cases} \tag{2}$$

where r is the reflection coefficient.

[15] Parallel velocities $v_\parallel \equiv (\vec{v}, \vec{B}/B_0) \leq 0$ in equation (2) correspond to the incoming ion flow in the northern hemisphere and refracted ion flow in the southern one. The particles with $v_\parallel > 0$ at $z \geq 0$ are reflected from the CS plane towards their plasma source.

[16] Figure 1 illustrates this scheme. Our presentation (2) of the distribution function is close to the one used before in papers by *Chen* [1992] and *Holland et al.* [1996]. The distribution function in the source was taken in the form:

$$f(v) = \frac{n_0}{2\left(\sqrt{\pi} v_T\right)^3 (1 + erf(v_D/v_T))} \exp\left\{-\frac{\left(v_\parallel - v_D\right)^2 + v_\perp^2}{v_T^2}\right\}. \tag{3}$$

[17] Asymmetry of the original source distribution is determined by the ratio $\varepsilon = v_T/v_D$ [*Sitnov et al.*, 2000; *Zelenyi et al.*, 2000] (v_T is the thermal velocity, v_D is the drift flow velocity) and as we mentioned above we will consider below only realistic case $\varepsilon \leq 1$.

[18] To find the ion distribution function at any position over the entire current sheet one can represent it as a function of invariants of motion: the total particle energy $mv_0^2/2 = m(v_x^2 + v_y^2 + v_z^2)/2$ and the approximate integral of motion $I_z = (m/2\pi)\, v_z dz$ (introduced by *Speiser* [1965] and *Sonnerup* [1971]). This procedure was described in details, for example, in the papers by *Sitnov et al.* [2000] and *Zelenyi et al.* [2000]. Introducing the normalized variables $\zeta = z\omega_0/\varepsilon^{4/3} v_D$, $\vec{w} = \vec{v}/(v_D \varepsilon^{2/3})$, $w_0^2 = w_x^2 + w_y^2 + w_z^2$, $\vec{X} = \vec{X}/(\omega_0 v_D \varepsilon^{4/3})$, $I = I_z \varepsilon^{2/3} \omega_0/(m_i v_T^2)$, $b = B_x/B_0$ (here $\omega_0 = eB_0\, eB_0\, mc$) one can present the distribution function in a form

$$f\left(w_0^2, I\right) \sim \exp\left(-\varepsilon^{-2/3}\left(\left[\sqrt{w_0^2 - I} - \varepsilon^{-2/3}\right]^2 + I\right)\right) \tag{4}$$

[19] The Liouville theorem then allows one to rewrite the self-consistent Vlasov-Maxwell equation (1) in a simple form:

$$\frac{db}{d\zeta} = \frac{4\varepsilon}{\pi^{3/2}[1 + erf(\varepsilon^{-1})]} \left(\frac{v_D}{v_A}\right)^2 \cdot \int w_y \exp\left(\varepsilon^{-2/3}\left(\left[\sqrt{w_0^2 - I(\vec{w}, \zeta)} - \varepsilon^{-2/3}\right]^2 + I(\vec{w}, \zeta)\right)\right) d^3w \tag{5}$$

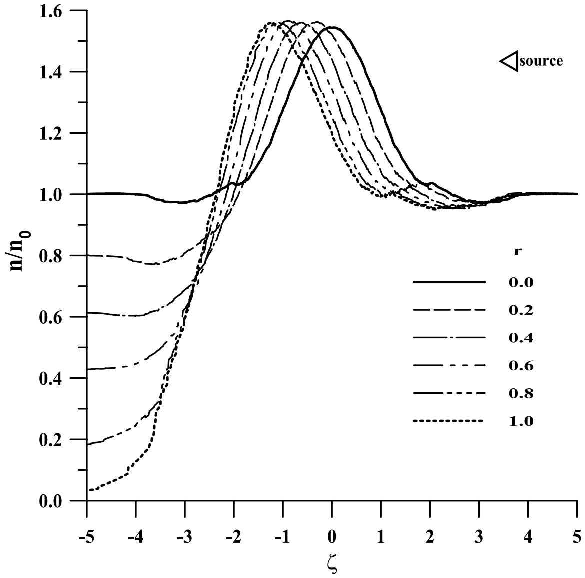

Figure 2. Plasma density as a function of the coordinate z in GSM system of reference. Parameter r is the reflection coefficient which is changed from 0% to 100% with step 20%, parameter of anisotropy of plasma source $\varepsilon = 1$.

with the boundary condition $b(-\infty) = -1$ only in the southern lobe of magnetotail $z \leq 0$ where there is no plasma source in our model. Here v_A is the Alfven velocity. Contrary to the symmetric case where the magnetic fields at both boundaries were specified $b(\pm\infty) = \pm 1$ we have free boundary now at $z > 0$ and the boundary value $b(+\infty)$ will be found in calculations. Also it is important to note that even for a fully reflective case: $r = 1$ particle penetrate to the other side of field reversal plane because of the meandering character of their motion in a "crossing" regime. So a layer thickness is determined by the amplitude of meandering particle oscillations. Finally we will solve numerically the system of the equations (2)–(5) and will find self-consistent equilibrium solutions for magnetic field B_x, current density j_y and plasma density n in dependence on the asymmetry parameter r.

4. Results and Conclusions

[20] The system of equations (2)–(3) for self-consistent asymmetric CS supplied from only one plasma source in the northern mantle was solved numerically using an iteration procedure [*Zelenyi et al.*, 2004a, 2004b]. Figure 2 demonstrates the dependence of the self-consistent profiles of the plasma density from the reflection coefficient r.

[21] The symmetrical case is $r = 0$ (ion flow crosses CS without any reflection).

[22] The pattern changes if r becomes larger: plasma gets more dense at the side of the source due to superposition of the incoming and reflected plasma flows and more rarefied at the opposite side (where only part of the initial flow of particles could pass through the sheet). Figure 2 shows a set of $n(z)$ profiles calculated for $r = 0.0, 0.2, 0.4, 0.6, 0.8, 1.0$. The corresponding profiles of the magnetic field and current density for different values of parameter r are presented in Figures 3a and 3b. The profiles of the magnetic field are normalized on their asymptotic value at the southern lobe.

[23] One can see in these figures that the current density profile becomes visually asymmetric.

[24] Large negative "wings" appear at the $\zeta > 0$ side of the source. They might be understood as an enhancements of the negative diamagnetic current due to the pile-up of the partial plasma density of non-crossing particles at this side (Figure 2). Very significant fraction of the current across the sheet is supported by meandering parts of ion trajectories, crossing alternatively regions where $B_x(z) \geq 0$ and $B_x(z) < 0$. This explains the "stickiness" of the position ζ_m of $J_{max}(\zeta_m)$ to the field reversal plane where $B_x(\zeta^*) = 0$. Even for the most asymmetric case ($r = 1$) the positions ζ_m and ζ^* do not differ dramatically: $|\zeta_m - \zeta^*| \leq (0.1-0.2)\ \rho_{0i}$. This is illustrated at the upper left insert at Figure 3b. Very

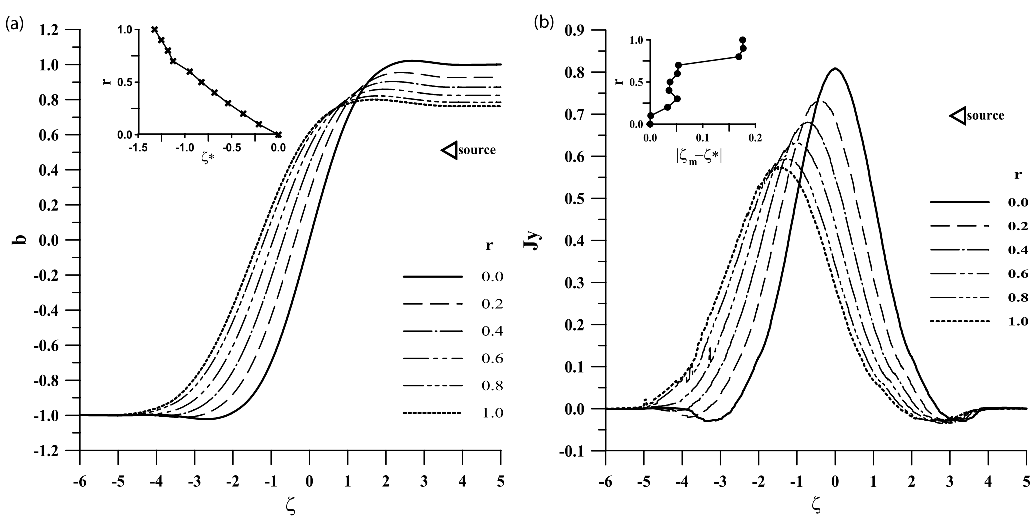

Figure 3. (a) Magnetic field and (b) current density profiles for various reflection coefficients r at $\varepsilon = 1$. Small panels at upper left corners are displacement of the zero plane z^* ($B_x(z^*) = 0$) (Figure 3a) and relative displacement of the positions z^* and current maximum z_m (Figure 3b).

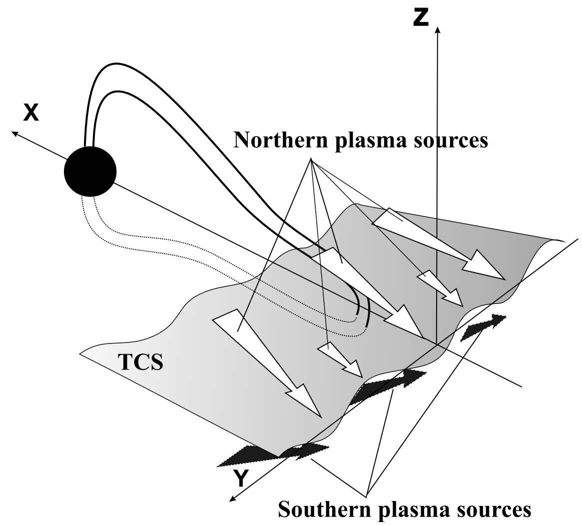

Figure 4. Possible mechanism of generation of kink-like CS perturbations due to deviation of the minimum of the magnetic field z^* from symmetrical position.

important changes occur with the position of the magnetic field reversal ζ^*. The displacement of ζ^*, where $B_x(\zeta^*) = 0$ is shown at the left insert at Figure 3a. Displacement occurs in the direction opposite to the position of the source and could be quite substantial $\zeta^* \sim \rho_i(\Delta\ \zeta^*) \leq 1.5\ \rho_i$ for strongest asymmetry $r = 1$.

[25] As we claim here such offset is probably rather general feature of CS, required by the pressure balance condition in z-direction $p_{zz}(z) + B_x^2(z)/8\pi = const$. The excess of plasma pressure at the source side shifts the $B_x(z)$ profiles to the left which results in the offset of the position of the current reversal z^* (shown in Figure 3a).

[26] One may attempt to use our asymmetric current sheet model for explanation of current sheet flapping which was recently studied thoroughly by CLUSTER [*Runov et al.*, 2006]. Flapping is very important dynamical effect in magnetotail especially during active times [*Sergeev et al.*, 2003]. We could speculate that up and down motions of CS might be induced by the transient asymmetries of plasma sources in northern and southern hemisphere.

[27] Accordingly [*Sergeev et al.*, 2004], the appearance of any inhomogeneity of plasma sources near the midnight meridian could produce current sheet kink-like distortions propagating towards flanks of the magnetotail. We suppose that the generation of "forced kink perturbations" will be more effective if the inhomogeneity acts on the current sheet near the midnight part of the tail. Current sheet becomes more diffusive towards flanks and presumably less subjected to the influence of the external sources.

[28] Figure 4 illustrates this idea. Needless to say that the real dynamics of these forced flapping motions and their characteristic spatial and temporal scales require much more sophisticated quantitative analysis, which we plan to do incorporating dynamics and 2D effects into our model.

[29] As we mentioned above the deviation of the current density maximum ζ_m from the position z^* of the minimum of magnetic field ($B_x(\zeta^*) = 0$) is really very small ($\leq (0.1 - 0.2)\rho_i$ even for $r \to 1$). The smallness of this difference is due to the fact that main portion of the cross-tail current is carried by almost symmetrical meandering parts of ion orbits and the asymmetry is mostly supported by the diamagnetic currents at the edges of TCS. Therefore, our model in principle does not describe large deviations between the planes of maximum of cross-tail current and the plane of the minimum of the magnetic field. It should be noted, nevertheless, that in some asymmetric sheets observed in experiment [*Runov et al.*, 2006] this difference might be somewhat larger $\sim \rho_i$.

[30] The main point of our paper is that self-consistent kinetic theory could account for at least one class of asymmetric cross tail current profiles, which, according to our knowledge, have not been discussed in literature thus far. Detailed comparison of theoretical results and Cluster data requires additional analysis due to a large variety of sheets with asymmetric but qualitatively different profiles. Neither of these sheets could be described by standard Harris model or even our earlier anisotropic symmetrical current sheet model. Our asymmetric anisotropic CS model conforms with data much better especially if additional electron contributions are taken into account. The results of this comparison will be reported in another publication.

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